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6. AUTHOR(S) David H. Allen and Dimitris C. Lagoudas	
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13. ABSTRACT *(Maximum 200 words)*

This report details the most recent accomplishments that have lead towards the fulfillment of the grant objectives. These achievements include: 1) life prediction of continuous fiber metal matrix composites; 2) the influence of heat treatment on the mechanical properties and damage development in a SiC/Ti-15-3 MMC; 3) the experimental characterization of oxidation on fracture surfaces and crack growth behavior; 4) modeling the effects of oxidation on the crack growth resistance of metals; and 5) the modeling of oxidation fronts in metals. In summary, the development of a low-cycle life prediction model that has the capability to account for the effect of surface oxidation on life of Titanium matrix MMC's is complete. The research performed herein concluded that the life of the composite appears to be controlled by interface debonding and subsequent radial cracking. The work performed under this grant also included a program to experimentally characterize the morphology of TiO2, one of the primary stoichiometric oxides formed during oxidation of titanium, in order to develop more accurate oxide layer growth models. It has been shown that specimen geometry plays a significant role in the rate of oxide growth. The last phase of this research effort was to develop and numerically implement a mathematical model of oxidation for metals with the capability of modeling complex oxidation fronts, such as they arise in MMC's. The oxidation of metals has been modeled by modifying the Fickian diffusion problem in order to simulate the chemical reaction (phase change) in the metal. The current model is capable of solving 1D and 2D oxidation problems in metallic domains with complex geometry.

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Micromechanism Based Modeling of Structural Life in Metal Matrix Composites

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ABSTRACT

AFOSR Grant F49620-94-1-0341

This report details the most recent accomplishments that have lead towards the fulfillment of the grant objectives. These achievements include: 1) life prediction of continuous fiber metal matrix composites; 2) the influence of heat treatment on the mechanical properties and damage development in a SiC/Ti-15-3 MMC; 3) the experimental characterization of oxidation on fracture surfaces and crack growth behavior; 4) modeling the effects of oxidation on the crack growth resistance of metals; and 5) the modeling of oxidation fronts in metals.

In summary, the development of a low-cycle life prediction model that has the capability to account for the effect of surface oxidation on life of Titanium matrix MMC's is complete. The research performed herein concluded that the life of the composite appears to be controlled by interface debonding and subsequent radial cracking. These cracks appear to be driven by a combination of two factors: the development of a surface layer consisting primarily of stoichiometric TiO_2 which induces a dilatational eigenstrain; and the embrittlement of material at the metal-oxide interface. In addition, the influence of various heat treatments on the mechanical behavior of SiC/Ti 15-3 MMC was also investigated. The study revealed that the heat treatments effected the overall composite compliance and damage accumulation. A model was also developed during this phase of the research, which successfully simulates the stress versus strain response of the composite accounting for both plastic deformation and damage.

The work performed under this grant also included a program to experimentally characterize the morphology of TiO_2, one of the primary stoichiometric oxides formed during oxidation of titanium, in order to develop more accurate oxide layer growth models. As part of this effort, the growth and structure of the TiO_2 oxide layer, monolithic samples of high purity titanium and Ti-15-3 were oxidized in air at 700°C for time lengths as short as 1 hour to a maximum of 168 hours. It has been shown that specimen geometry plays a significant role in the rate of oxide growth. In addition, the surface oxidation characteristics of Ti-15-3 MMC while undergoing crack extension was investigated. Results of the monotonic tension experiments on pre-cracked-then oxidized-then tested specimens indicate that the oxide layer generally has little effect on the bulk behavior of the material. As part of this effort, numerical model was also developed which is capable of simulating the effect of the oxide layer on the crack growth resistance of metals. It is believed that such a model could be used to facilitate the study of the static and fatigue strength of fractured metal in an oxidizing environment. Two different methods of fracture mechanics modeling (i.e. the isoparametric and the crack closure method) were evaluated in order to simulate the mechanical response of a pre-cracked pre-oxidized specimen. The current model is capable of describing the effect of the stiffer oxide and the oxide layer volumetric expansion to the energy release rate. It has been found that the combination of these two oxide scale properties causes the energy release rate to decrease when a thin layer if oxide is present and to increase for a thick oxide layer.

The last phase of this research effort was to develop and numerically implement a mathematical model of oxidation for metals with the capability of modeling complex oxidation fronts, such as they arise in MMC's. The oxidation of metals has been modeled by modifying the Fickian diffusion problem in order to simulate the chemical reaction (phase change) in the metal. The current model is capable of solving 1D and 2D oxidation problems in metallic domains with complex geometry. Simulations of the oxide scale growth from the crack surfaces in a Ti-15-3 specimen with a semi-infinite crack, a complex geometry crack-tip, as well as the scale growth on cylindrical and wedge-like domain geometries have been successfully performed.

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AFOSR Grant F49620-94-1-0341
Final Progress Report
March 23, 1998

Status of Effort/Accomplishments/New Findings:

The objectives of this research effort were to: 1) develop a micromechanics and thermodynamics based model for predicting macroscopically averaged thermomechanical constitutive behavior of continuous fiber metal matrix composites (MMC's); 2) develop and test MMC's experimentally to determine microscopic variables that are necessary to develop the micromechanics model mentioned in 1); and 3) carry out a limited experimental program for model verification. In the following subsections, key accomplishments which have lead towards the fulfillment of the aforementioned objectives, are briefly summarized.

Life Prediction of Continuous Fiber Metal Matrix Composites:

The development of a low-cycle life prediction model that has the capability to account for the effect of surface oxidation on life of Titanium matrix MMC's is complete. We have observed in our own experiments (See Fig. 1) that life is reduced by a factor of five in SCS-6/Ti-β21S tested at 650°C when the composite was tested in air rather than inert gas (Argon). The life of the composite appears to be controlled by interface debonding and subsequent radial cracking, as shown in Fig. 2. This reduction in life appears to be the result of surface cracks which develop on the specimen when tested in air, as demonstrated in the SEM photo shown in Fig. 3. These cracks appear to be driven by a combination of two factors: the development of a surface layer consisting primarily of stoichiometric TiO_2 which induces a dilatational eigenstrain; and the embrittlement of material at the metal-oxide interface. The net effect of these surface features is an overall reduction in the critical energy release rate for the system. Using these observations and assumptions, we have developed a finite element model which utilizes a representative volume element (RVE) for the laminate tested above, as shown in Fig. 4. As described in our recent papers, the mesh incorporates the surface oxide layer, as well as the dilatational eigenstrain in order to capture the life reduction mechanism. As shown in Fig. 5, for the case of monotonic loading, the model does produce a reduced stress-strain behavior for the composite due to the development of surface cracks. Figures 6 and 7 demonstrate a comparison of the predicted results for cyclically loaded unoxidized and oxidized SCS-6/Ti-β21S $[0]_4$ specimen at 650°C, respectively.

Influence of Heat Treatment on the Mechanical Properties and Damage Development in a SiC/Ti-15-3 MMC:

The purpose of this study was to investigate the influence of possible heat treatments on the mechanical behavior of SiC/ Ti 15-3 MMC, as well as characterize the deformation and damage mechanisms. The effects of three heat treatment conditions on the thermomechanical response and damage development in unidirectional axial and transverse specimens were investigated. A four ply uni-directional SiC/Ti-15-3 MMC was tested in the axial and transverse direction and the damage evolution at both room temperature and at 427 °C was observed. The thermomechanical study revealed that the heat treatments effected the overall composite compliance and damage accumulation.

In addition, averaging micromechanical models were utilized to simulate the effect of matrix damage and plasticity on the mechanical response of the composite. A model based on the Mori-Tanaka method was developed and implemented which combines both plasticity and damage in an incremental formulation. Model predictions were then compared to experimental results through microstructural evaluation of matrix crack densities.

Mechanical tests show that the 450°C heat treatment creates a microstructure with a consistently high elastic modulus and high damage tolerance for all loading conditions and temperatures. Microstructural evaluation identified the primary damage modes for both the transverse and axial specimens. The axial specimens showed evidence of cracks developing perpendicular to the loading direction starting from the fiber/matrix interface (see Fig. 8). The transverse specimens showed cracks emanating from areas of poor consolidation resulting in cracks propagating in the loading direction along grain boundaries. The model developed during this research initiative successfully simulates the stress versus strain response of the composite accounting for both plastic deformation and damage (see Fig. 9). In addition, a prediction of the crack density was made as a function of overall applied load. It was shown that the predicted crack density at the final load level over predicts the crack densities measured from a post-test microstructural analysis for the transverse specimens (see Fig. 10). It was believed that the over prediction was most likely due to pre-existing matrix/fiber damage.

Experimental Characterization of Oxidation on Fracture Surfaces and Crack Growth Behavior:

The purpose of this research was to experimentally characterize the morphology of TiO_2, one of the primary stoichiometric oxides formed during oxidation of titanium, in order to develop more accurate oxide layer growth models. In addition, this phase of the research included the preliminary design and development of a test methodology which will allow for real time evaluation of crack growth behavior in an elevated temperature (25°to 700°C) and oxidizing (air) environment.

As part of the effort to characterize the growth and structure of the TiO_2 oxide layer, monolithic samples of high purity titanium and Ti-15-3 were oxidized in air at 700°C for time lengths as short as 1 hour to a maximum of 168 hours. Various specimen geometry's were oxidized and then analyzed using SEM. Geometry's investigated include: the inside radius of a small diameter hole ($\approx$300 μm); the outside radius of a small diameter wire ($\approx$140μm); and a flat edge which included a corner. In addition, in order to gain insight on how the oxide layer would effect crack growth behavior and material fracture toughness, a series of experiments were conducted wherein, samples of high purity titanium were pre-cracked to a predetermined length using a fully reversed low cycle fatigue load. The crack in each specimen was wedged open and then either heat treated (in an inert environment) or oxidized at 700°C for 24 to 48 hours. Each specimen was then subjected to a monotonic tensile load were visual and tabular data were recorded for later analysis.

It has been shown that specimen geometry plays a significant role in the rate of oxide growth, as shown in Fig. 11. However, additional insight was needed in order to understand the complex strain field that appears to be present in the oxide layer during formation, as well as the predominate diffusion mechanism. Figures 12 a)-d) show typical oxide scale developed during oxidation at 700°C. The surface oxidation characteristics of Ti-15-3 MMC while undergoing crack extension is shown in Fig. 12d). The photograph indicates how oxide scale from the matrix develops around the exposed sigma fibers. Figure 13 shows how an oxide layer develops on the fracture surface during oxidation. Results of the monotonic tension experiments on pre-cracked-then oxidized-then tested specimens indicate that the oxide layer generally has little effect on the bulk behavior of the material (Fig. 14). Figure 15 a)-c) indicates that the oxide generally fractures at loads substantially below that which are required for crack growth extension of the material considered herein.

Modeling the Effects of Oxidation on the Crack Growth Resistance of Metals:

The purpose of the research was to develop a numerical model capable of simulating the effect of the oxide layer on the crack growth resistance of metals. It was envisioned that such a model would then be used to facilitate the study of the static and fatigue strength of fractured metal in an oxidizing environment.

Two different methods of fracture mechanics modeling (i.e. the isoparametric and the crack closure method) were evaluated in order to simulate the mechanical response of a pre-cracked pre-oxidized specimen. Validation of the methods is accomplished by comparing numerical results with an analytical solution for a crack in a homogeneous material (see Fig 16), as well as crack-tip extending through a heterogeneous. Two physical characteristics of the oxide scale (i.e. the stiffness change and the volumetric expansion) were as input in the parametric numerical studies. In particular, the effect of these two parameters on the energy release rate was evaluated for a monotonically loaded, pre-cracked, compact tension specimen at room temperature.

The current model is capable of describing the effect of the stiffer oxide and the oxide layer volumetric expansion to the energy release rate. It has been found that the combination of these two oxide scale properties causes the energy release rate to decrease when a thin layer if oxide is present and to increase for a thick oxide layer, as shown in Fig.17. An FEM model was also used to simulate a monotonic tension test on a CT style specimen that was preoxidized. Comparison to experimental results is shown in Fig. 18.

Modeling of Oxidation Fronts in Metals:

The purpose of this research was to develop and numerically implement a mathematical model of oxidation for metals with the capability of modeling complex oxidation fronts, such as they arise in MMC's.

The oxidation of metals has been modeled by modifying the Fickian diffusion problem in order to simulate the chemical reaction (phase change) in the metal. The resulting mathematical model consists of two parabolic differential equations and metal-oxide interface conditions. Two different variants of a fixed grid finite element method for numerical simulation of the oxidation process have been used. The first approach (the discrete interface method) taken was to locate the oxidation front and split the domain into metal and oxide subdomains. The second approach (the smearing front method) is based on reformulating the diffusion equations in both the oxide and metal, resulting in a single non-linear equation for the whole domain. Figures 19 and 20 show a comparison between numerical and analytical results for oxide layer thickness and oxygen concentration profiles, respectively.

The current model is capable of solving 1D and 2D oxidation problems in metallic domains with complex geometry. Validated numerical models have been used to simulate the oxide scale growth from the crack surfaces in a Ti-15-3 specimen with a semi-infinite crack (see Fig. 21), a complex geometry crack-tip (see Fig 22), in addition to scale growth on cylindrical and wedge-like domain geometries.

Personnel Supported

Faculty:	D.H. Allen D.C. Lagoudas
Graduate Students:	J. Foulk K.L.E. Helms R. Triharjanto P.K. Imbrie D. Miller P. Entchev
Undergraduate:	R. S. Nah G.D. Seidel

Journal Publications

JEONG, G.S., ALLEN, D.H., and LAGOUDAS, D.C., 1994, "Residual Stress Evolution due to Cool-Down in Viscoplastic Metal Matrix Composites," International Journal of Solids and Structures 31 No. 19, pp. 2653-2677.

WITTIG, L.A., and ALLEN, D.H., "Effect of Oxidation on SiC/Ti-15-3 Metal Matrix Composites," Journal of Engineering Materials and Technology, Vol. 116, pp. 421-427, July 1994.

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Lagoudas, D.C., Ma, X., Miller, D.A., and Allen, D.H., 1995, "Modeling of Oxidation in Metal Matrix Composites," International Journal of Engineering Science 33, pp. 2327-2343.

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COSTANZO, F., BOYD, J.G., ALLEN, D.H., "Micromechanics and Homogenization of Inelastic Composite Materials with Growing Cracks," Journal of Mechanics and Physics of Solids, Vol. 44, No. 3, pp. 333-370, 1996.

XU, G.-M., LAGOUDAS, D.C., HUGHES, D., and WEN, J.T., 1997, "Modeling of a Flexible Beam Actuated by Shape Memory Alloys Wires," Journal of Smart Materials and Structures 6, No.3., pp. 265-277.

Allen, D.H., Lo, D.C., and Zocher, M.A., "Modeling of Damage Evolution in Laminated Viscoelastic Composites," International Journal of Damage Mechanics, Vol. 6, pp. 5-22, 1997.

Accepted Journal Publications

Lagoudas, D.C., and Ding, Z., 1996, "Domain Transformation Techniques in Oxygen Diffusion Problems with a Moving Oxidation Front on Bounded Domains," International Journal of Engineering Science.

LAGOUDAS, D.C., MA, X., and XU, S., 1997, "Surface Damage of Oxidized Metal Matrix Composite Laminates Under Transverse Tension," International Journal of Damage Mechanics.

DING, Z., and LAGOUDAS, D.C., 1997, "A Domain Transformation Technique in Oxygen Diffusion Problems with Moving Oxidation Fronts on Unbounded Domains," International Journal for Numerical Methods in Engineering.

LAGOUDAS, D.C. and DING, Z., 1997, "Numerical Computation of Metal Oxidation Problems on Bounded Domains," International Journal of Engineering Science.

MILLER, D.A. and LAGOUDAS, D.C., 1997, "Influence of Heat Treatment on the Mechanical Properties and Damage Development in a SiC/Ti-15-3 MMC," ASME Journal of Engineering Mechanics and Technology.

FOULK, J.W., ALLEN, D.H., HELMS, K.L.E., "A Model for Predicting the Damage and Environmental Degradation Dependent Life of SCS-6/TI-B21S [0] Metal Matrix Composite," Mechanics of Materials, April 1997.

Submitted

LAGOUDAS, D.C., ENTCHEV, P., AND TRIHARJANTO, R., "Modeling of Oxidation and its Effect on Crack Growth in Titanium Alloys," submitted to Computer Modeling in Applied Mechanics and Engineering, April 1998.

Conference Proceedings

MILLER, D.A., LAGOUDAS, D.C., and ALLEN, D.H., 1993, "Experimental Study of Damage Evolution in SiC/Ti Laminates with Different Heat Treatments, Proceedings of 4th International Symposium on Plasticity and its Current Applications, Baltimore MD, 19-23 July 1993.

JEONG, G.S., ALLEN, D.H., and LAGOUDAS, D.C., 1993, "Residual Stress Evolution due to Cool-Down in Viscoplastic Metal Matrix Composites," Thermomechanical Behavior of

Advanced Structural Materials, AD-Vol. 34, AMD-Vol. 173, W.F. Jones, ed., American Society of Mechanical Engineers, New York, pp. 17-31.

LAGOUDAS, D.C., ALLEN, D.H., and MA, X., 1994, "Modeling of Surface Oxidation and Oxidation Induced Damage in Metal Matrix Composites," Computational Material Modeling, AD-Vol. 42, PVP-Vol. 294, A.K. Noor and A. Needleman, eds., American Society of Mechanical Engineers, New York, pp. 245-264.

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LAGOUDAS, D.C., XU, S., MILLER, D., and ALLEN, D., 1996, "Damage in Oxidized Titanium Metal Matrix Composites," Proceedings of the ASME Aerospace and Materials Divisions, AD-Vol. 51, MD-Vol. 73., pp. 225-237.

Proceedings Volumes in Press

FOULK, J.W., HELMS, K.L.E, and ALLEN, D.H., "Life Prediction in Continuous Fiber Metal Matrix Composites," to appear in the proceedings of the American Society of Composites Annual Meeting," held in Dearborn, MI, October 1997.

FOULK, J.W., HELMS, K.L.E., and ALLEN, D.H., "Life Prediction in Continuous Fiber Metal Matrix Composites Subjected to Environmental Degradation," to appear in the proceedings of the 11th Technical Conference of the American Society of Composites, Atlanta, GA, October 7-9, 1996.

FOULK, J.W., HELMS, K.L.E., ALLEN, D.H., "A Computational Finite Element Analysis for Predicting the Effects of Environmental Degradation on Life in Metal Matrix Composites," to appear in the proceedings of the Symposium on Recent Developments in Engineering Science, 32nd SES Annual Technical Meeting, New Orleans, October 29-November 1, 1995.

ALLEN, D.H., HELMS, K.L.E., HURTADO, L., LAGOUDAS, D.C., "Prediction of Damage Evolution in Continuous Fiber Metal Matrix Composites Subjected to Fatigue Loading," to appear in the proceedings of the Symposium on Recent Developments in Engineering Science at the Society of Engineering Science (SES) 32nd Annual Technical Meeting, New Orleans, October 29-November 1, 1995.

ALLEN, D.H., FOULK, J.W., HELMS, K.L.E., and LAGOUDAS, D.C., 1997, "A Modeling for Predicting the Effect of Environmental Degradation on Damage Evolution in Metal Matrix Composites," Proceedings of the ASTM-STP Symposium on Applications of Continuum Damage Mechanics to Fatigue and Fracture.

FOULK, J.W., ALLEN, D.H., LAGOUDAS, D.C., 1997, "A Micromechanical Model for

Predicting Fatigue Response of Metal Matrix Composites Subjected to Environmental Degradation," Proceedings of the 1997 IUTAM Conference on Micromechanics of Composites and Active Materials.

LAGOUDAS, D.C., ENTCHEV, P., TRIHARJANTO, R., 1997, "Modeling of Oxidation and its Effect on the Crack Growth Resistance of Titanium Alloys," Damage Mechanics in Engineering Materials, Elsevier Science Publishers.

ALLEN, D.H., FOULK, J.W., HELMS, K.L.E., "Observation and Prediction of Damage Evolution in Continuous Fiber Titanium Matrix Composites," Proceedings of IMECE, Dallas, TX, November 1997.

Book Chapters

ALLEN, D.H., Eggleston, M.R., and HURTADO, L.D., "Recent Research on Damage Development in SiC/Ti Continuous Fiber Metal Matrix Composites," Fracture of Composites, E.A. Armanios, Ed., in Key Engr. Materials series, Vols. 120-121.

Interactions/Transitions

a. Participation/presentations at meetings, conferences, seminars, etc.

"Oxidation and Damage in Titanium Alloy Metal Matrix Composites," Sixth Annual Texas Fracture Discussion Group, Arlington, TX, February 9-10, 1995.

"Oxidation and Damage in Metal Matrix Composites," Mechanics and Materials Seminar, Texas A&M University, College Station TX, February 14, 1995.

"Impact Surface Oxidation on Damage Evolution in Metal Matrix Composites," ASME Joint Applied Mechanics and Materials Conference, Los Angeles, CA, June 28 – June 30, 1995.

"Modeling of Surface Oxidation in Metal Matrix Composites with Damage," Society of Engineering Science 32nd Annual Technical Meeting, New Orleans, LA, October 29 – November 2, 1995.

"Prediction of Damage Evolution in Continous Fiber Metal Matrix Composites Subjected to Fatigue Loading," to apper in the proceeding of the Symposium on Recent Development in Engineering Science, Society of Engineering Science (SES) 32nd Annual Technical Meeting, New Orleans, Oct. 29 - Nov. 1, 1995.

"Effects of Oxidation and Damage on the Fatigue Life of Metal Matrix Composites, 1995 International Mechanical Engineering Congress and Exposition, San Francisco, CA, November 12–17, 1995.

"The Effects of Oxidation and Damage on the Mechanical Response of Metal Matrix Composites," 1995 International Mechanical Engineering Congress and Exposition, San

Francisco, CA, November 12–17, 1995.

"Damage in Oxidized Titanium Metal Matrix Composites," 1995 International Mechanical Engineering Congress and Exposition, San Francisco, CA, November 12-17, 1995.

"Damage Evolution in Oxidized Metal Matrix Composite Laminates Under Axial and Transverse Unidirectional Tension," Society of Engineering Science 33rd Annual Technical Meeting, Tempe, AZ, October 20-23, 1996.

"Damage Development in Titanium Metal Matrix Composites in Oxidizing Environment," 1996 International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17-22, 1996.

"Surface Damage Modeling of Oxidized Metal Matrix Composite Laminates under Uniaxial Tension," 1996 International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17-22, 1996.

"A Model for Predicting the Effect of Environmental Degradation on Damage Evolution in Metal Matrix Composites,' ASTM Symposium on Applications of Continuum Damage Mechanics to Fatigue and Fracture, Orlando 1996.

"Development of a Micromechanically Based Damage Dependent Cohesive Zone Model and Its Application to Delamination in Viscoelastic Polymer Matrix Composites," ASME Summer Mechanics and Materials Conference, Baltimore, 1996.

"A Micromechanical Model for Predicting Environmentally Assisted Crack Growth in Continuous Fiber Metal Matrix Composites," ASME Summer Mechanics and Materials Conference, Baltimore, 1996.

"Prediction of Damage Evolution in Continuous Fiber Metal Matrix Composites Subjected to Fatigue Loading," ASME International Mechanical Engineering Congress and Exposition, Atlanta, 1996.

"A Micromechanical Model for Predicting Fatigue Response of Metal Matrix Composites Subjected to Environmental Degradation," IUTAM Symposium on Transformations in Composites, Cairo, Egypt, 1997.

"The Influence of Oxidation on Fatigue Crack Growth Behavior in Ti 15-3 Metal Matrix Composites," McNU '97 Joint Meeting of the ASME, ASCE and SES, Northwestern University, Evanston, IL, June 29 – July 2, 1997.

b. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories.

NASA Langley
Sandia National Laboratories

Lawrence Livermore National Laboratories

c. **Transitions. Describe cases where knowledge resulting from your effort is used, or will be used, in a technology application. Transitions can be to entities in the DoD, other federal agencies, or industry. Briefly list the enabling research, the laboratory or company, and an individual in that organization who made use of your research.**

Provided advice on damage evolution and life in MMC's to Dale L. Ball (Lockheed-Ft. Worth, TX).

New discoveries, inventions, or patent disclosures

None

Honors/Awards

D.H. Allen, President, Society of Engineering Science
D.C. Lagoudas, Treasurer, Society of Engineering Science, IDA - DSSG member

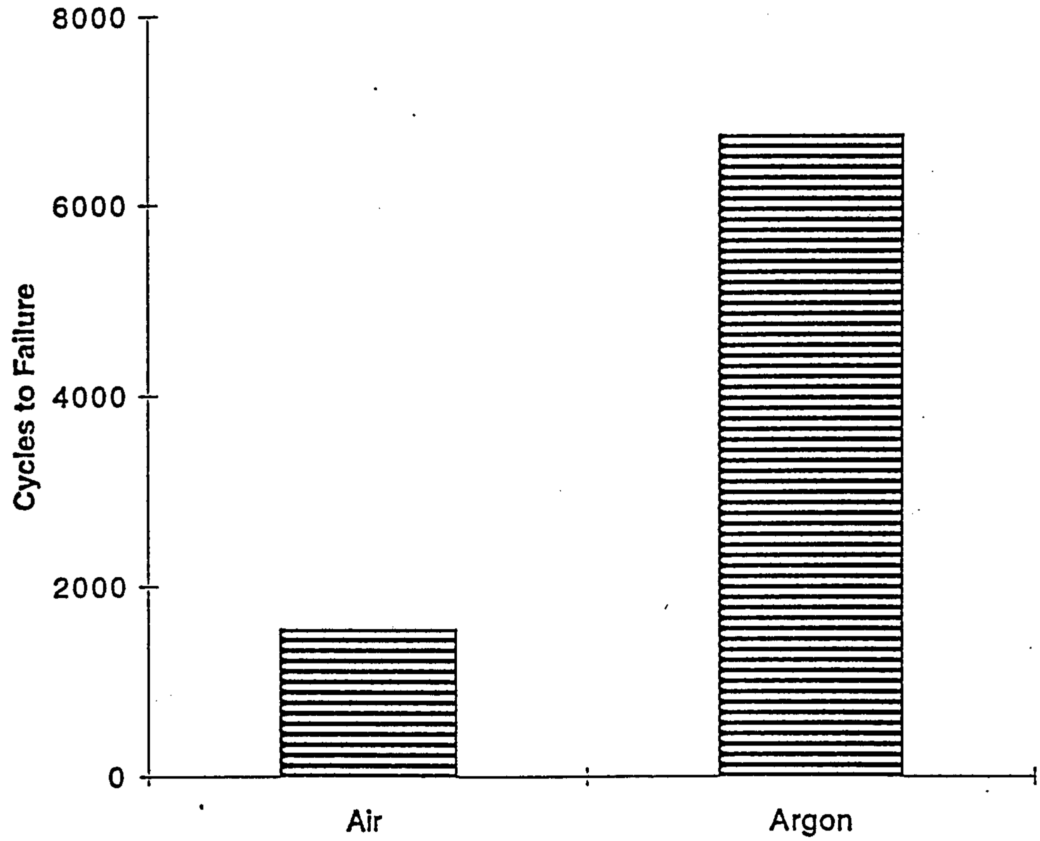


Figure 1. Fatigue life of SCS-6/Ti-β21S $[0]_4$ in air and argon at 650°C.

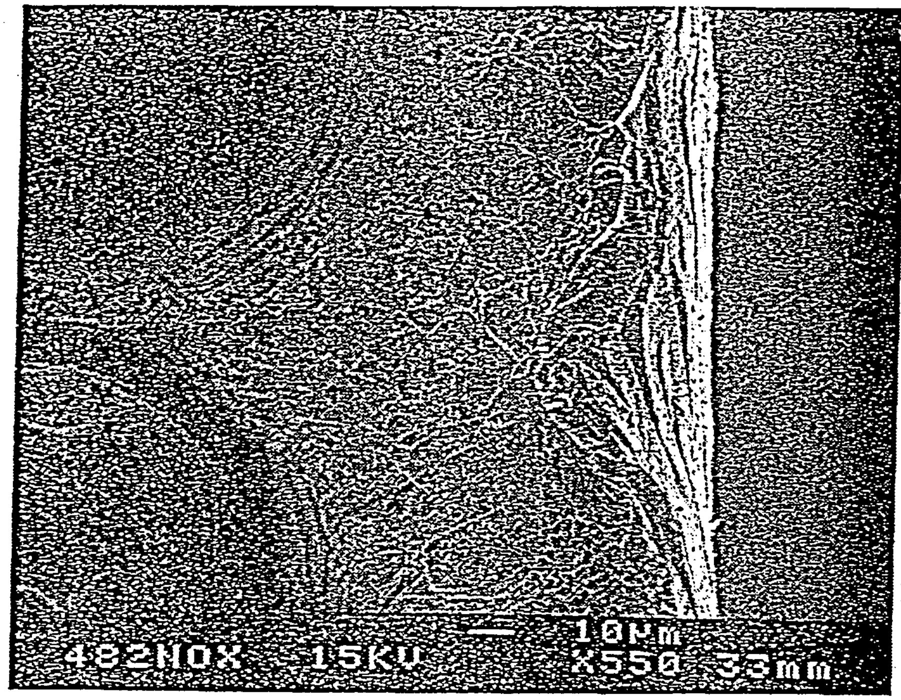


Figure 2. Fracture surface of unoxidized SCS-6/Ti-β21S $[0]_4$ fatigued at 482°C for 4000 cycles.

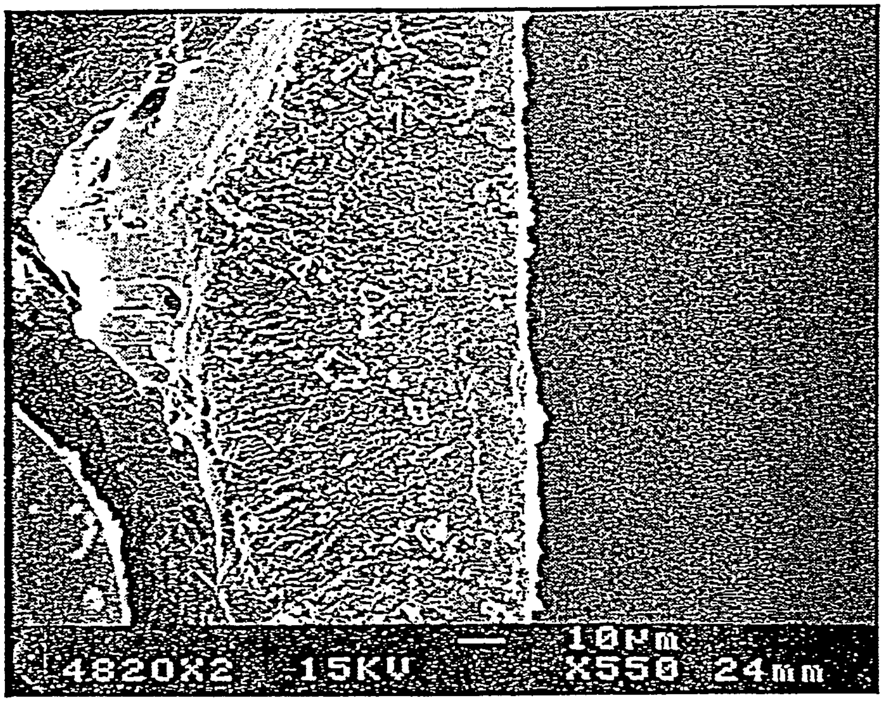


Figure 3. Surface crack propagating radially into the interior of SCS-6/Ti-β21S $[0]_4$. Confirmation of embrittled layer.

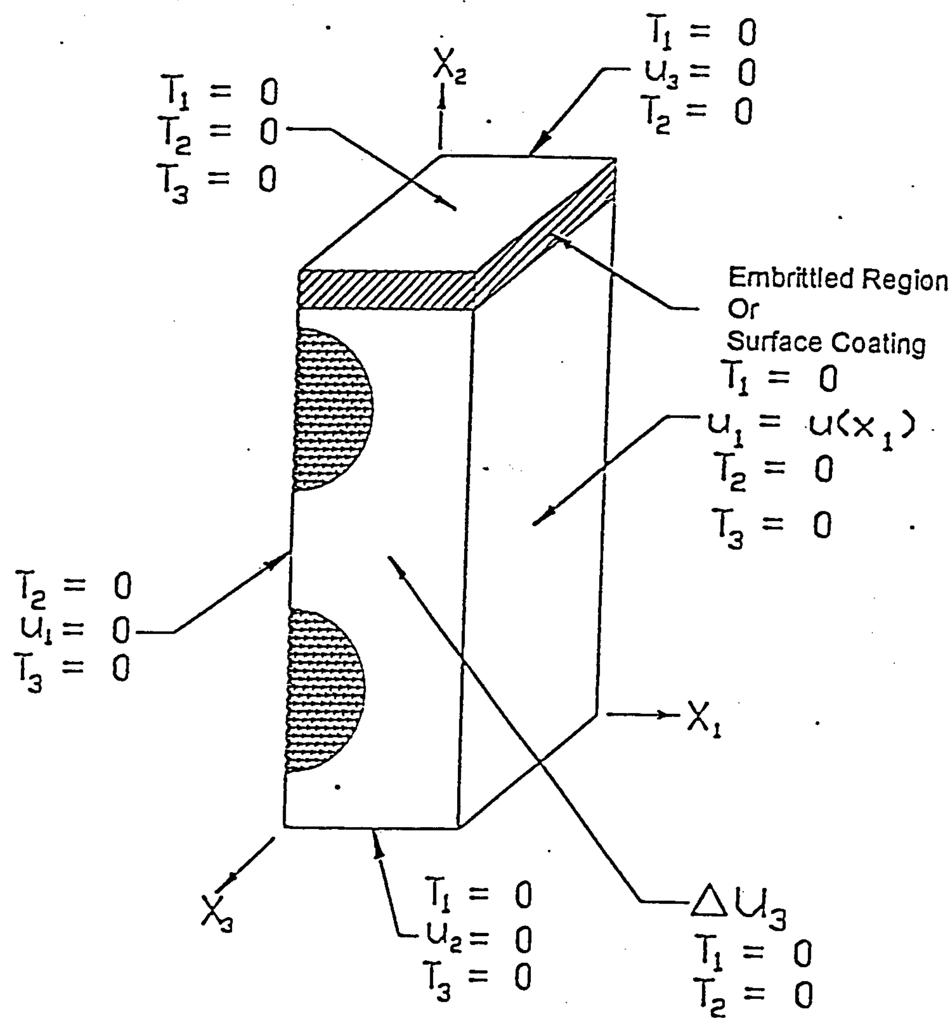


Figure 4. Representative Volume Element (RVE) of the SCS-6/Ti-β21S $[0]_4$ metal matrix composite. (Fiber volume fraction is 36%.)

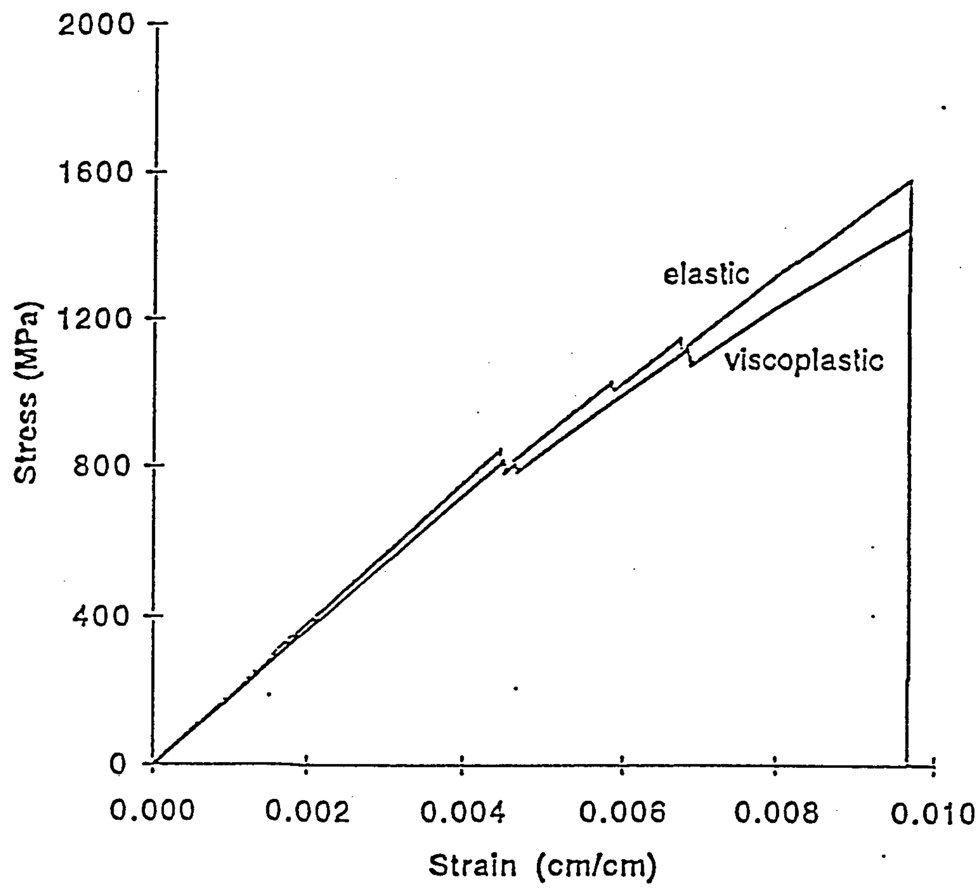


Figure 5. Comparison of elastic and viscoplastic analysis for monotonic loading of SCS-6/Ti-β21S $[0]_4$ at 650°C.

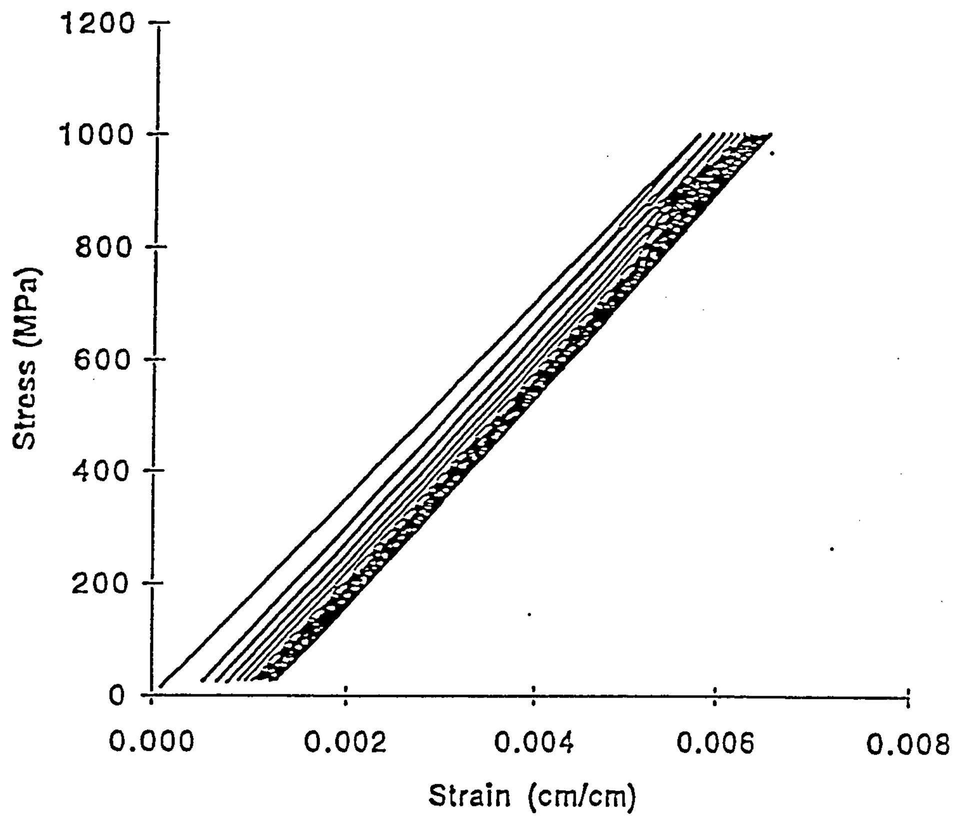


Figure 6. Predicted average stress vs. strain for cyclic loading of unoxidized SCS-6/Ti-β21S $[0]_4$ at 650°C (first 15 cycles).

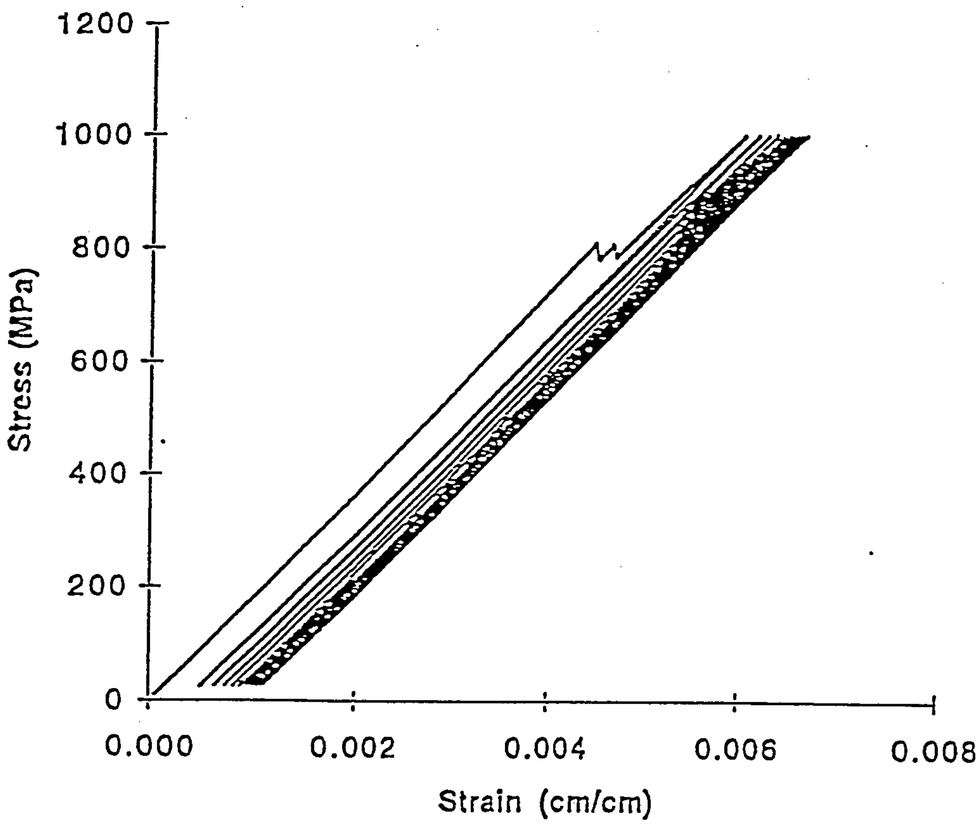
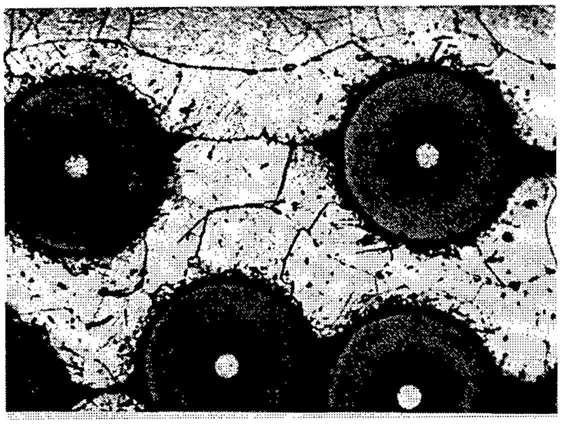
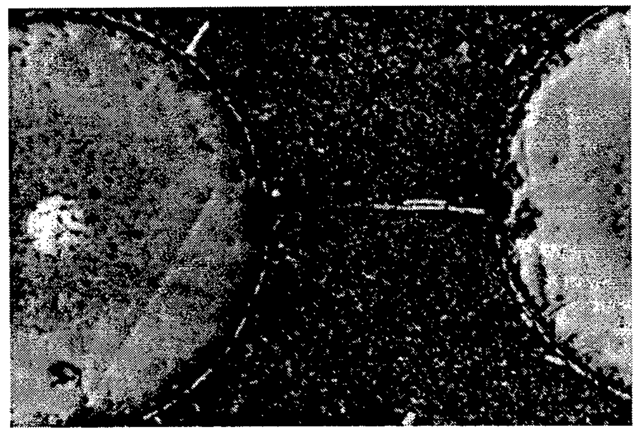


Figure 7. Predicted average stress vs. strain for cyclic loading of oxidized SCS-6/Ti-β21S $[0]_4$ at 650°C (first 14 cycles).



a) As-Received



b) 450°C for 24 hours

c) 700° C for 24 hours

Figure 8. Etched microstructure in transverse specimens of SiC/Ti-15-3 for each heat treatment showing dominant crack growth along grain boundary.

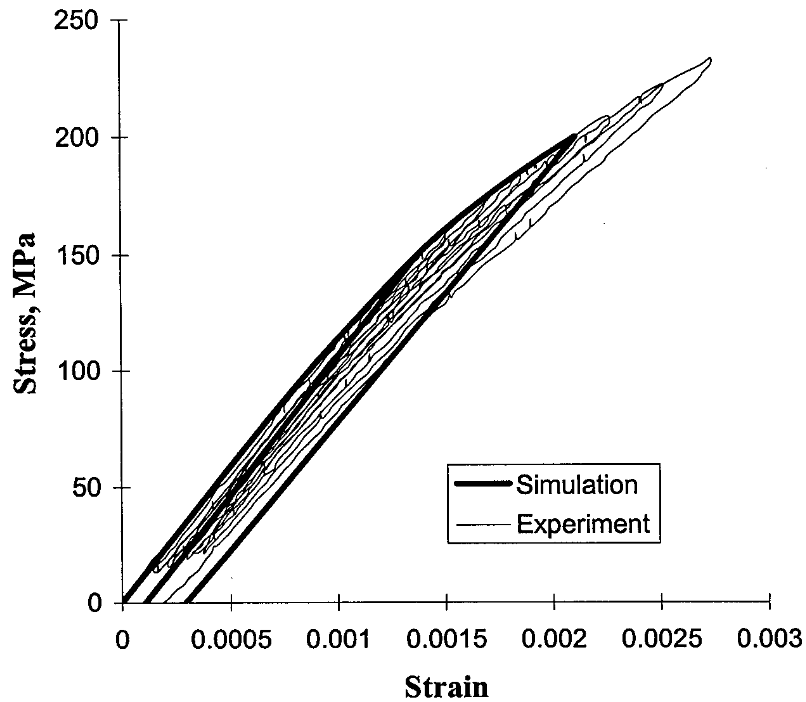


Figure 9. Stress vs. strain for transverse specimen of SiC/Ti-15-3 comparing simulation utilizing the crack density prediction and experimental data.

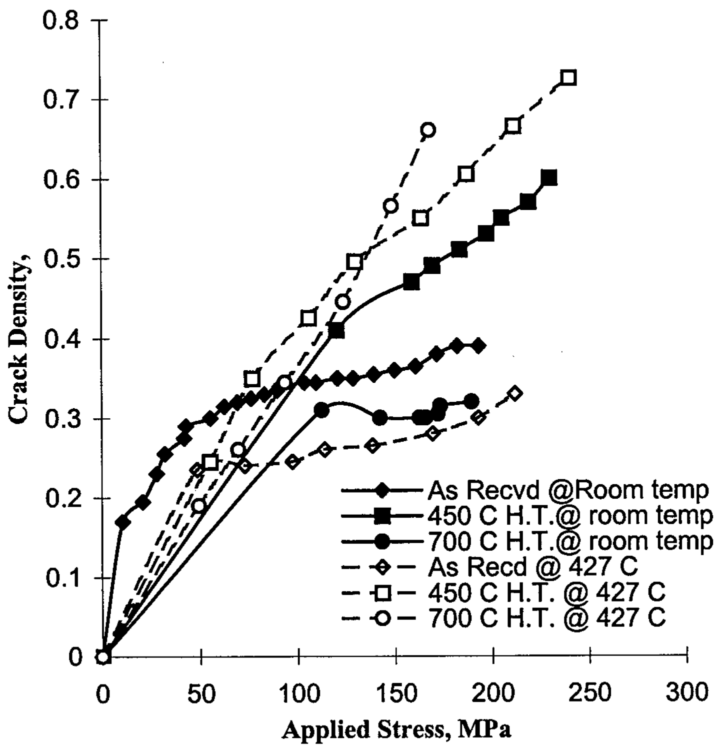


Figure 10. Prediction of crack density to applied stress for SiC/Ti-15-3.

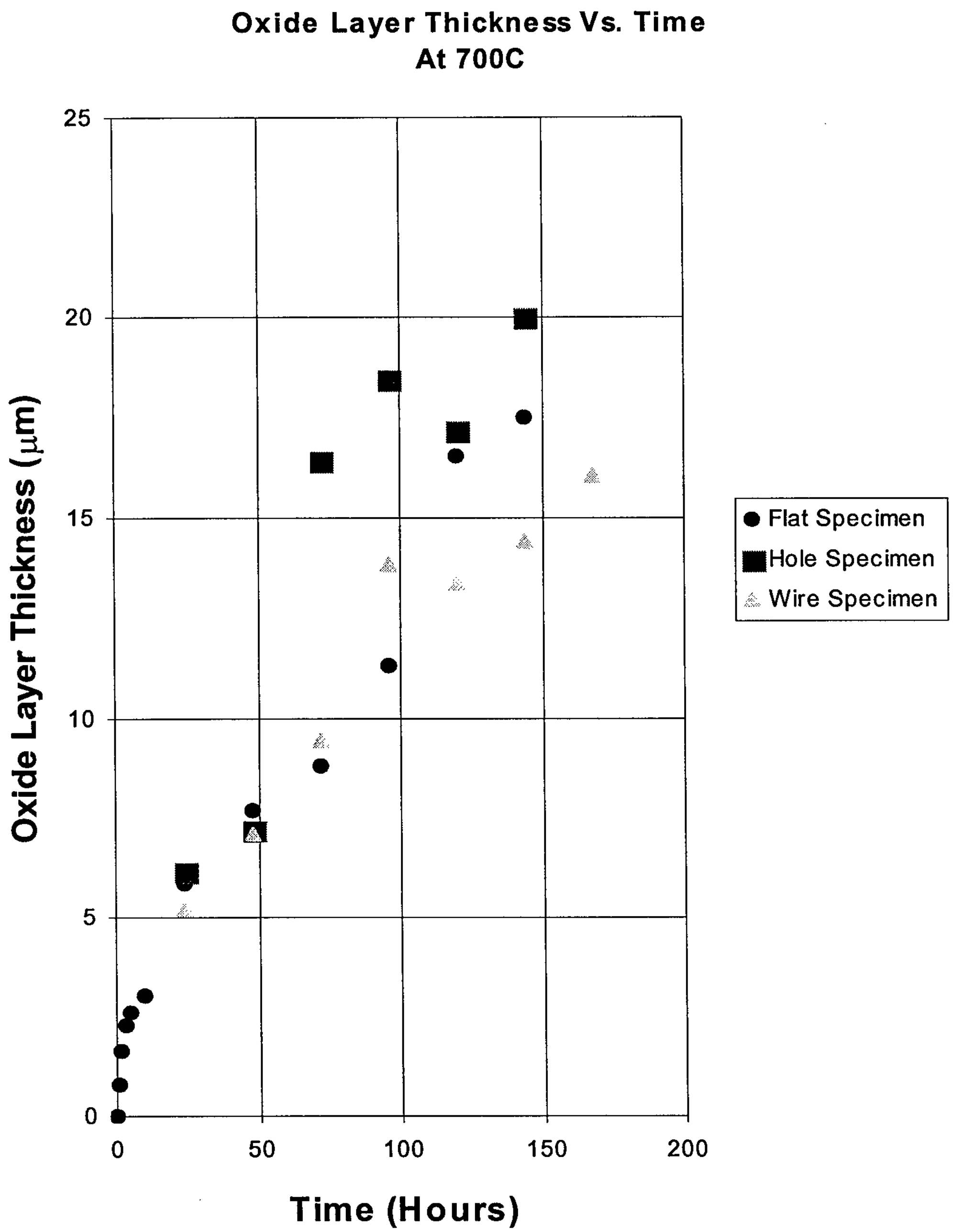
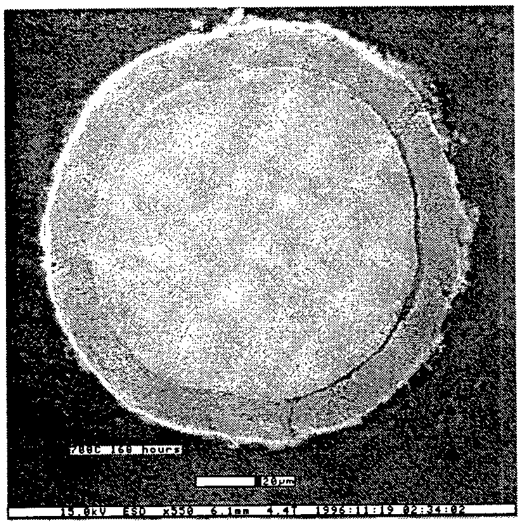
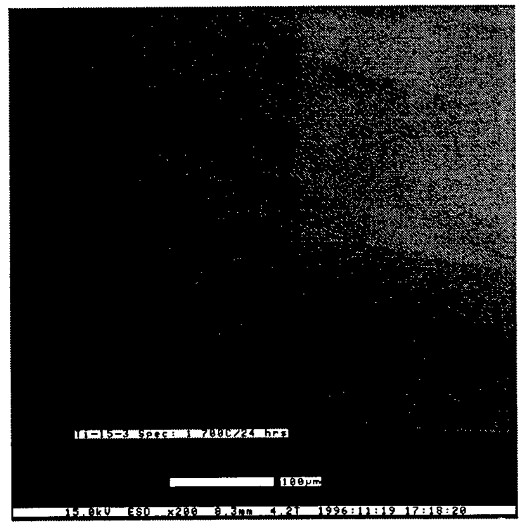


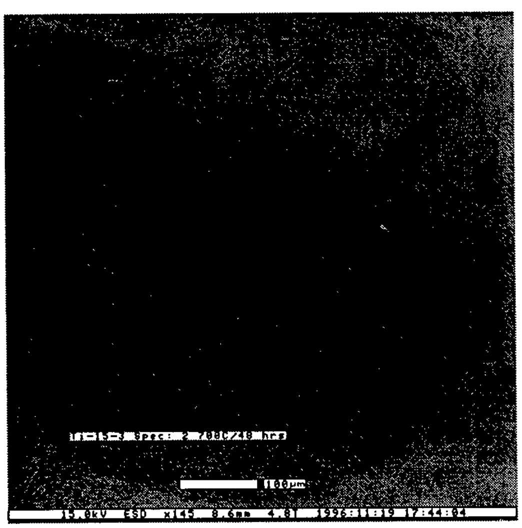
Figure 11. Oxide layer thickness as a function of time for various geometries of Ti at 700°C.



a) Wire Ti specimen oxidized for 168 hours.



b) Flat corner of Ti-15-3 specimen oxidized for 48 hours.



c) Hole in Ti-15-3 specimen oxidized for 48 hours.

d) 4 ply SiC/Ti-15-3 CT specimen oxidized for 10 hours at 700°C.

Figure 12. Various oxidized geometries at 700°C.

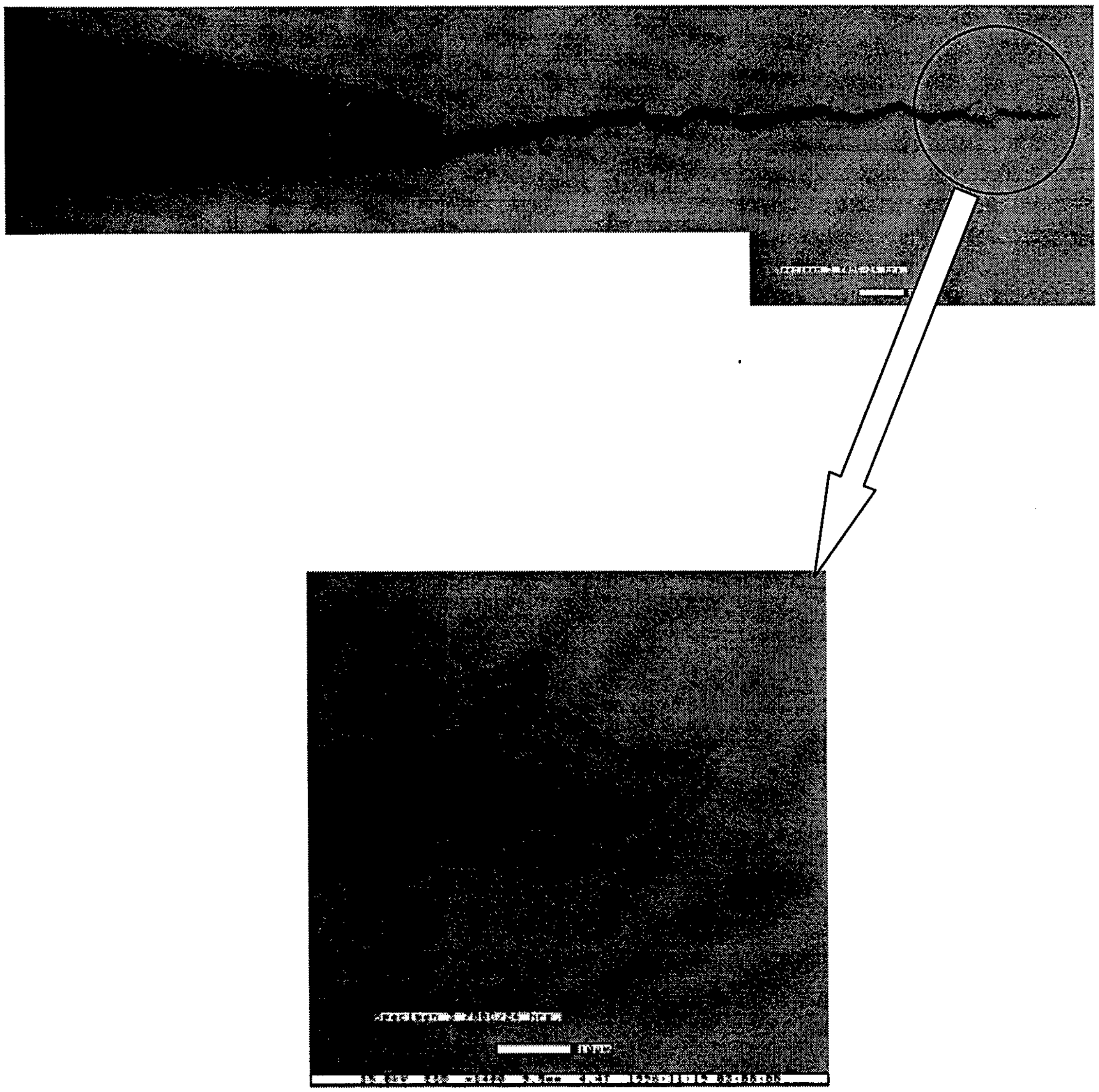


Figure 13. Macro crack in Ti that has been oxidized for 24 hours.

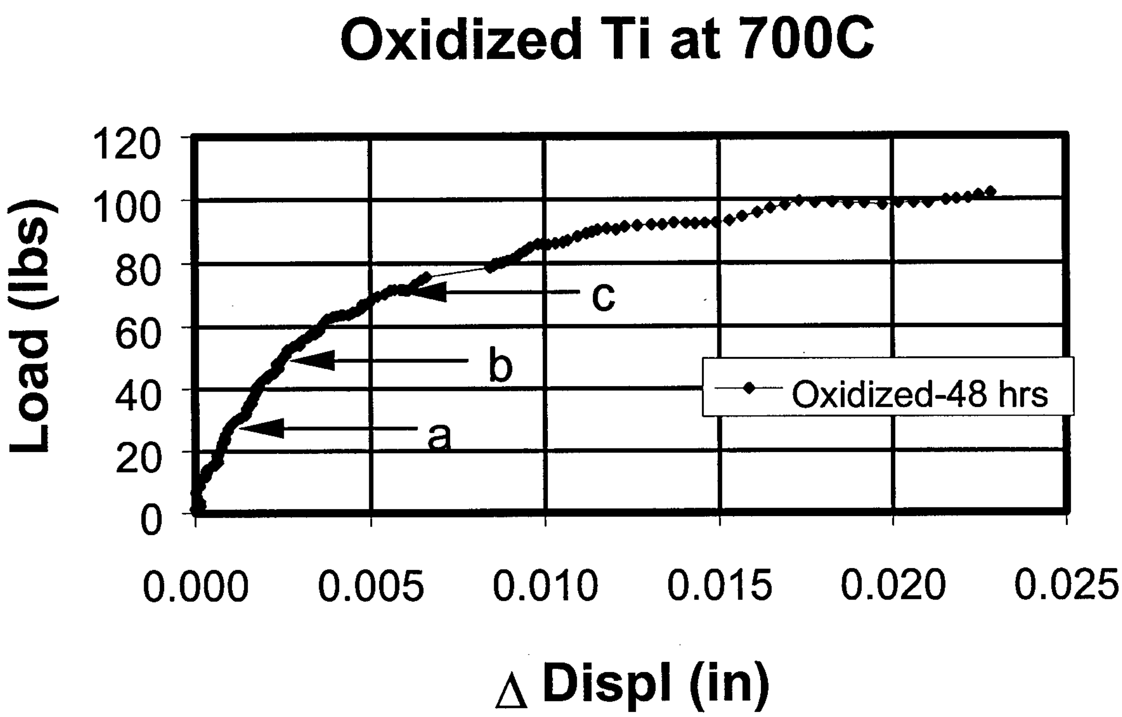


Figure 14. Crack opening displacement as a function of load for an oxidized Ti specimen. The points a,b, and c correspond to loading conditions of 30, 50, and 70 Lb.'s respectively as shown in Fig. 15.

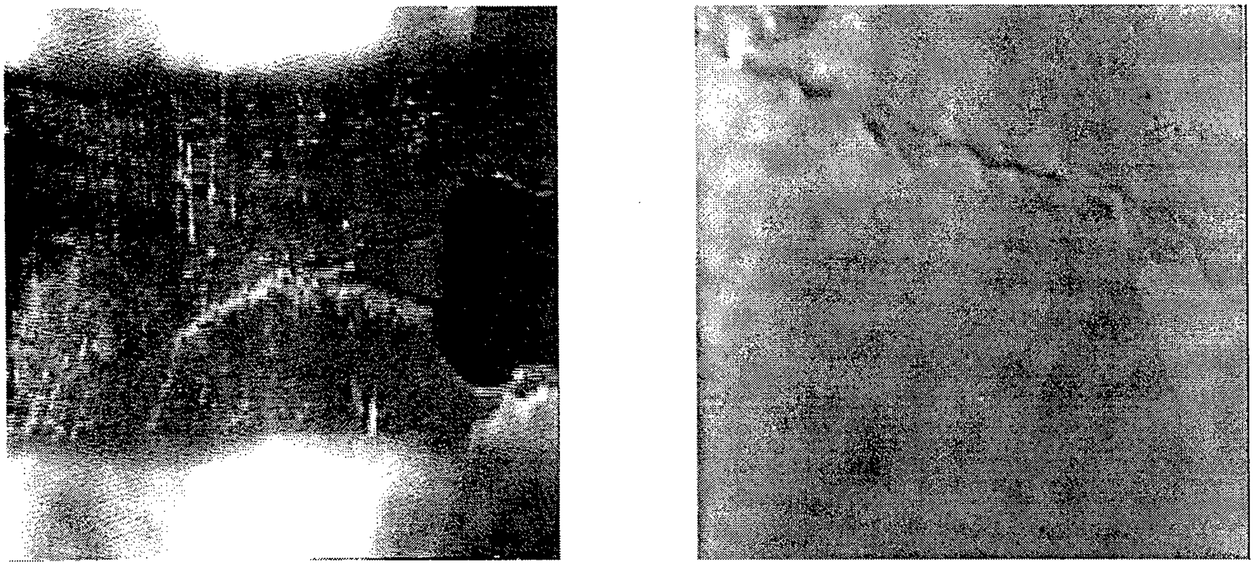


Figure 15. a)Fatigue crack in Ti subjected to a 30 Lb. load (point a in Fig. 14). Exposed surface (at left) and oxidized layer showing (at right).

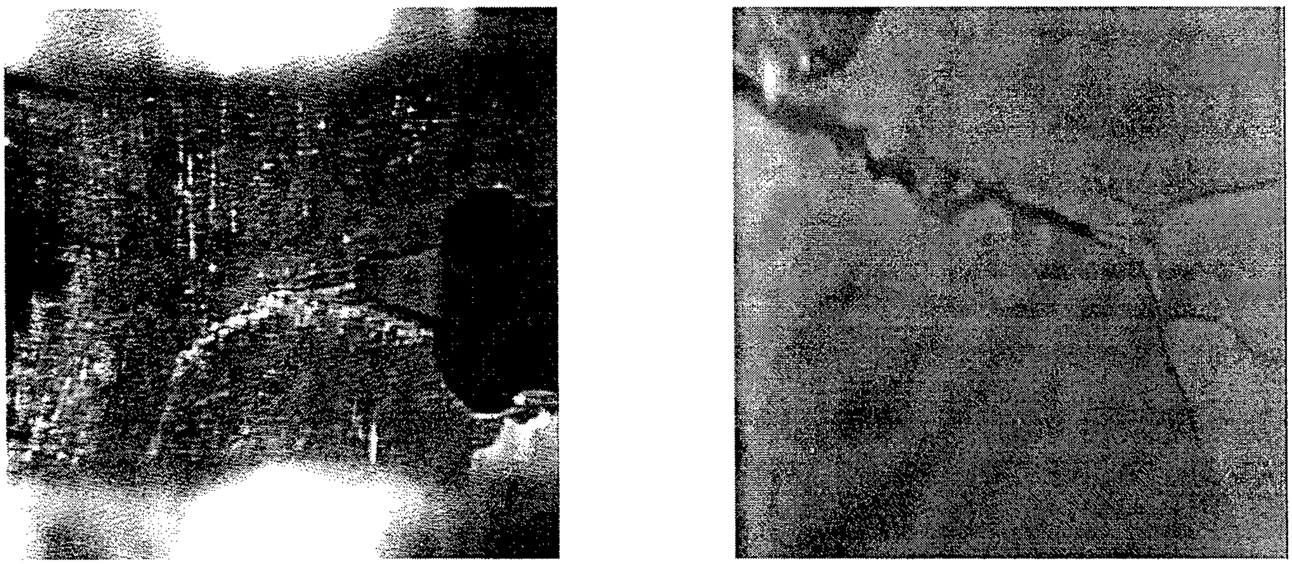


Figure 15. b) Fatigue crack in Ti subjected to a 50 Lb. load (point b in Fig. 14). Exposed surface (at left) and oxidized layer showing (at right).

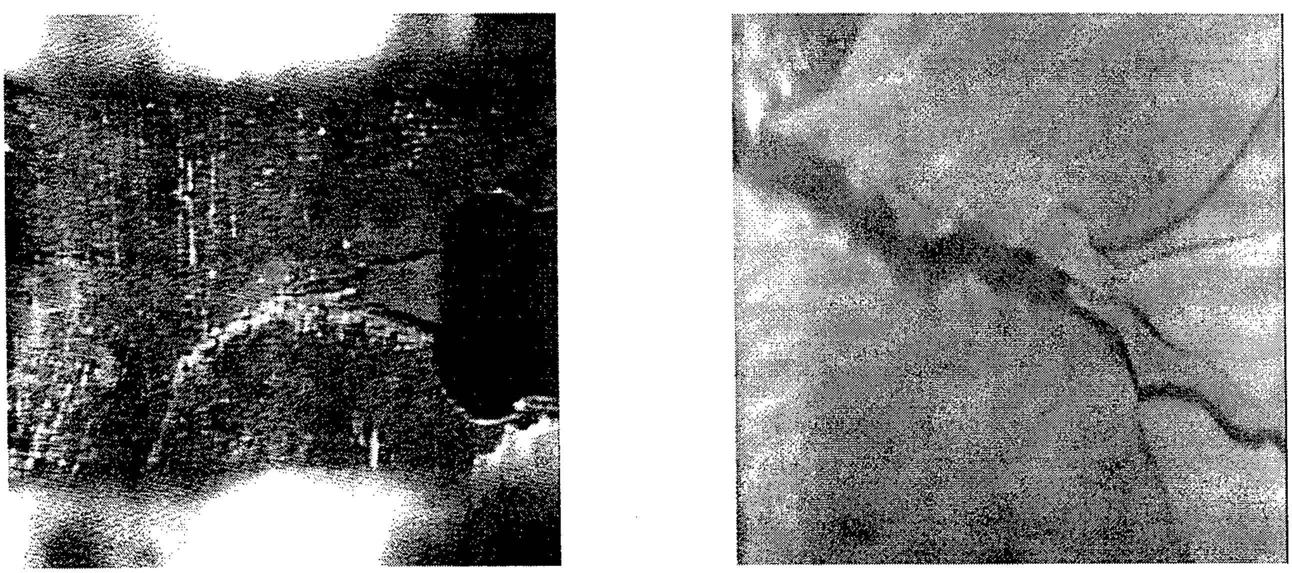


Figure 15. c) Fatigue crack in Ti subjected to a 70 Lb. load (point c in Fig. 14). Exposed surface (at left) and oxidized layer showing (at right).

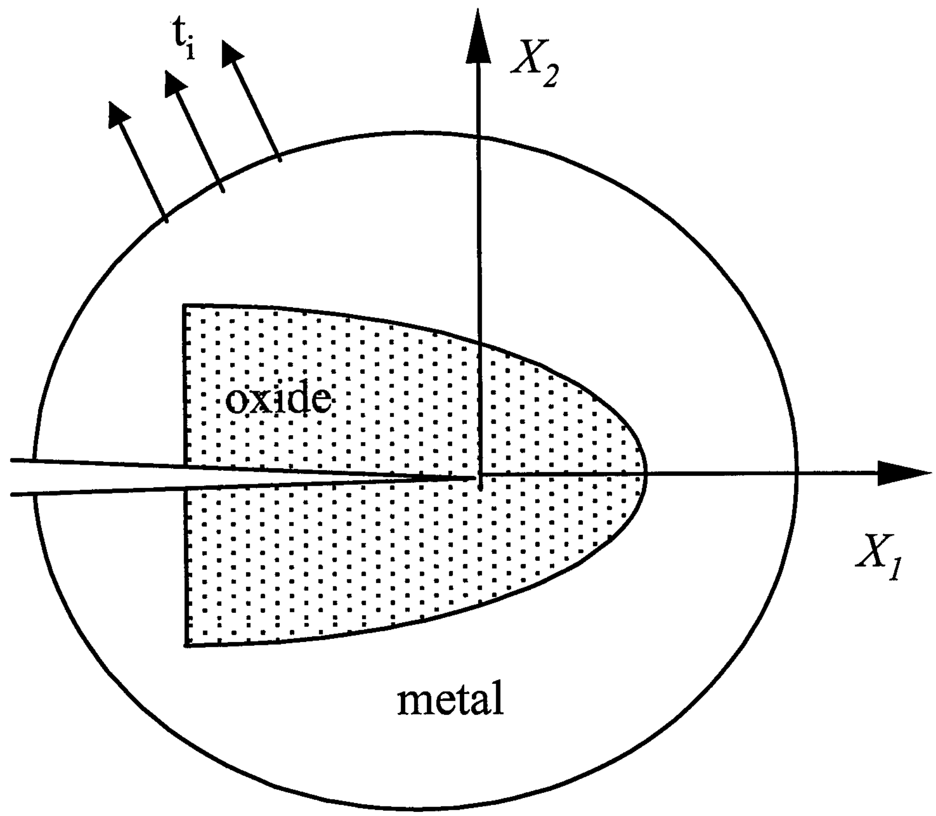


Figure 16. Simplified oxide geometry for the parametric studies assumes the crack to be planer and the oxide scale to be surrounded by unoxidized metal.

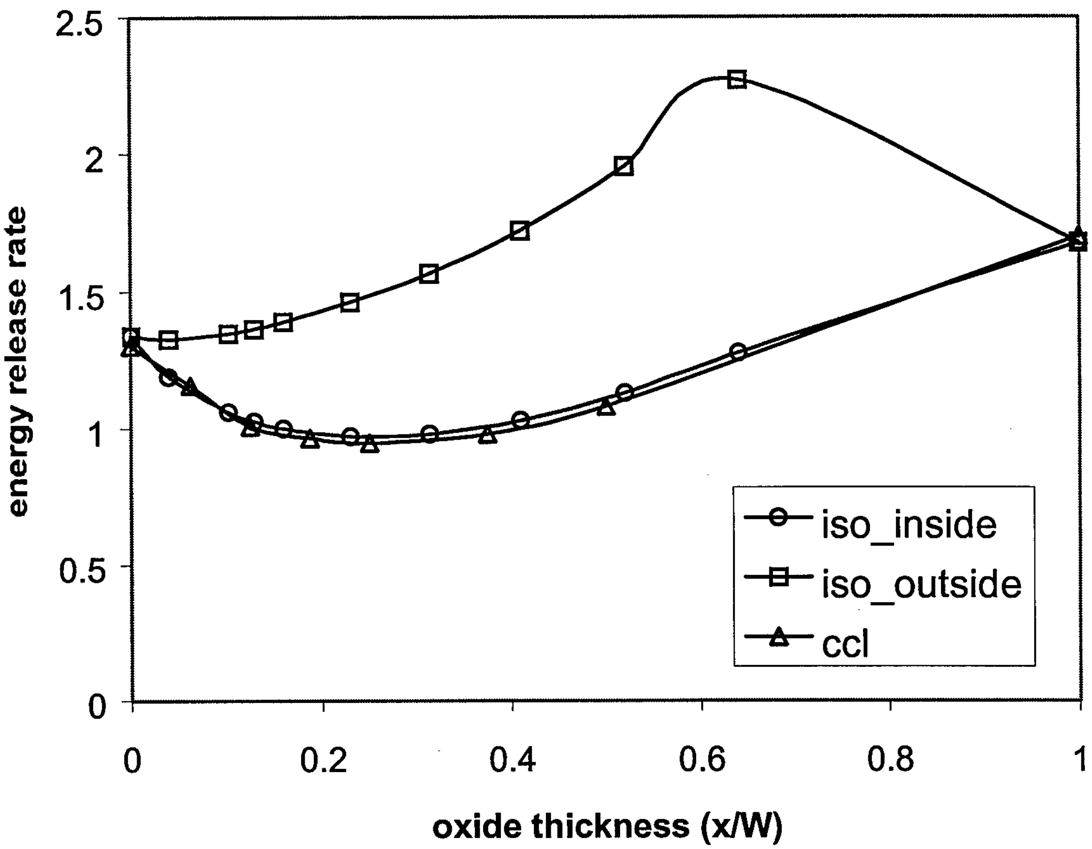


Figure 17. Numerical results showing the energy release rate calculated inside the oxide layer by the isoparametric method and the crack closure method.

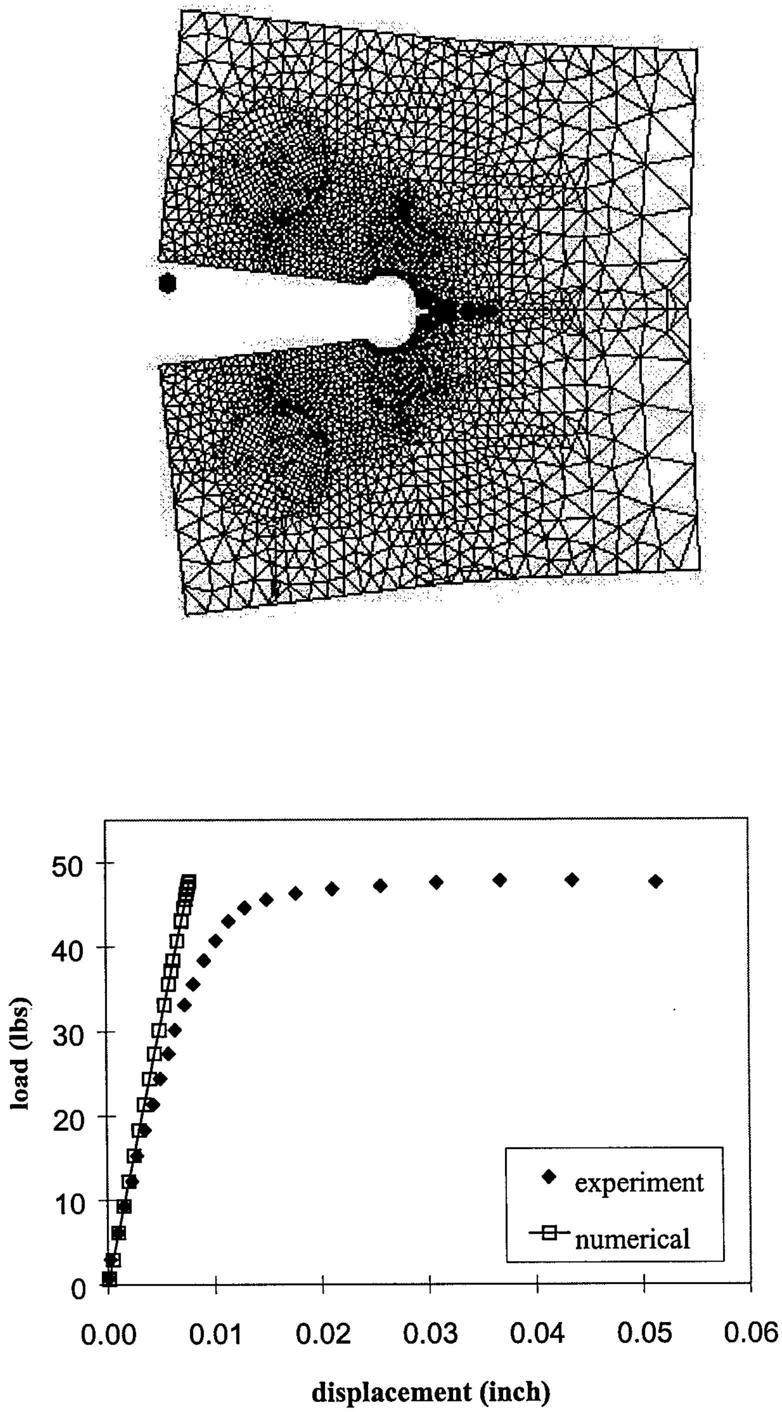


Figure 18. FEM model used to simulate monotonic test on an oxidized Ti CT specimen (above) and COD vs. load comparison (below).

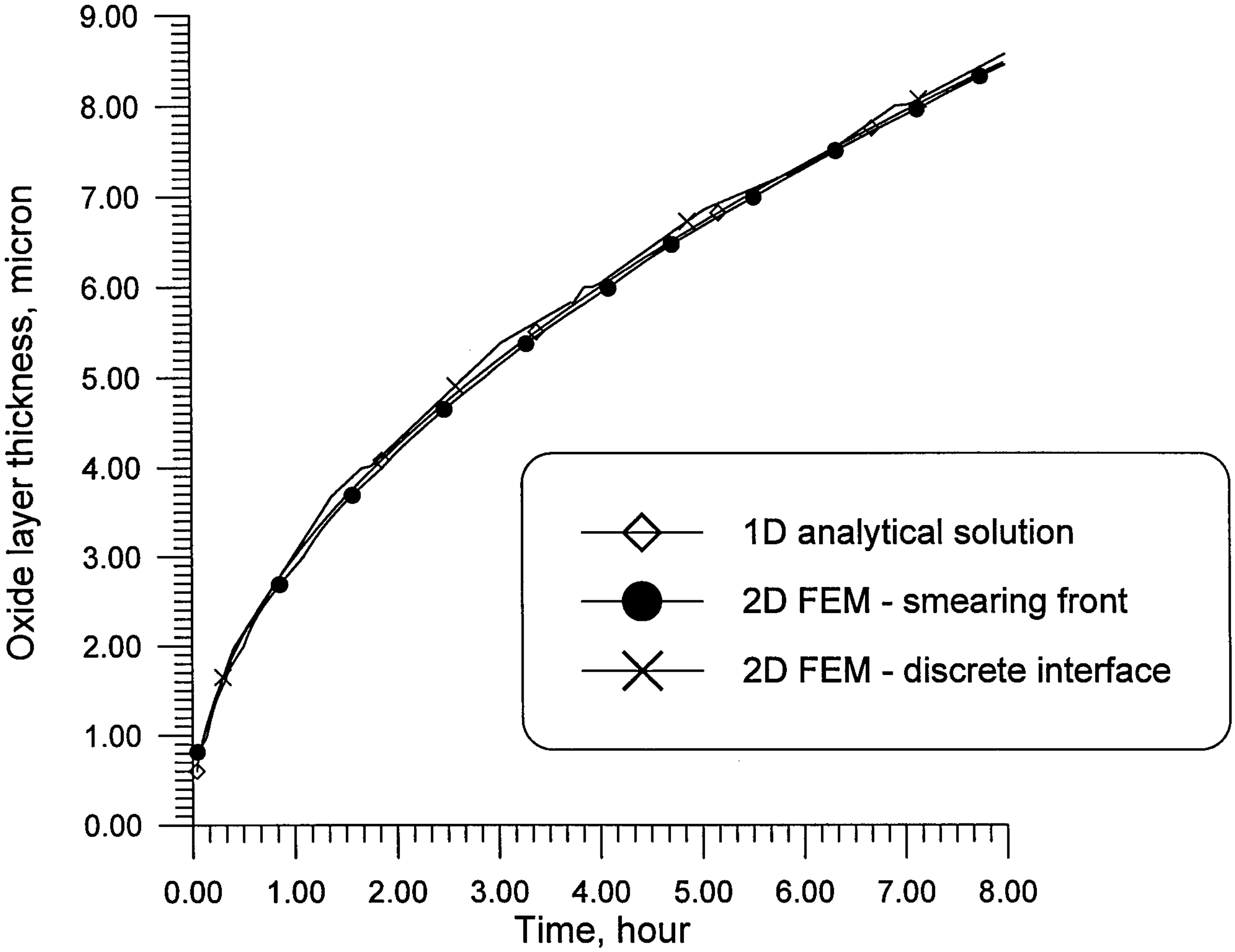


Figure 19. Comparison of numerical and analytical results for 1D oxidation.

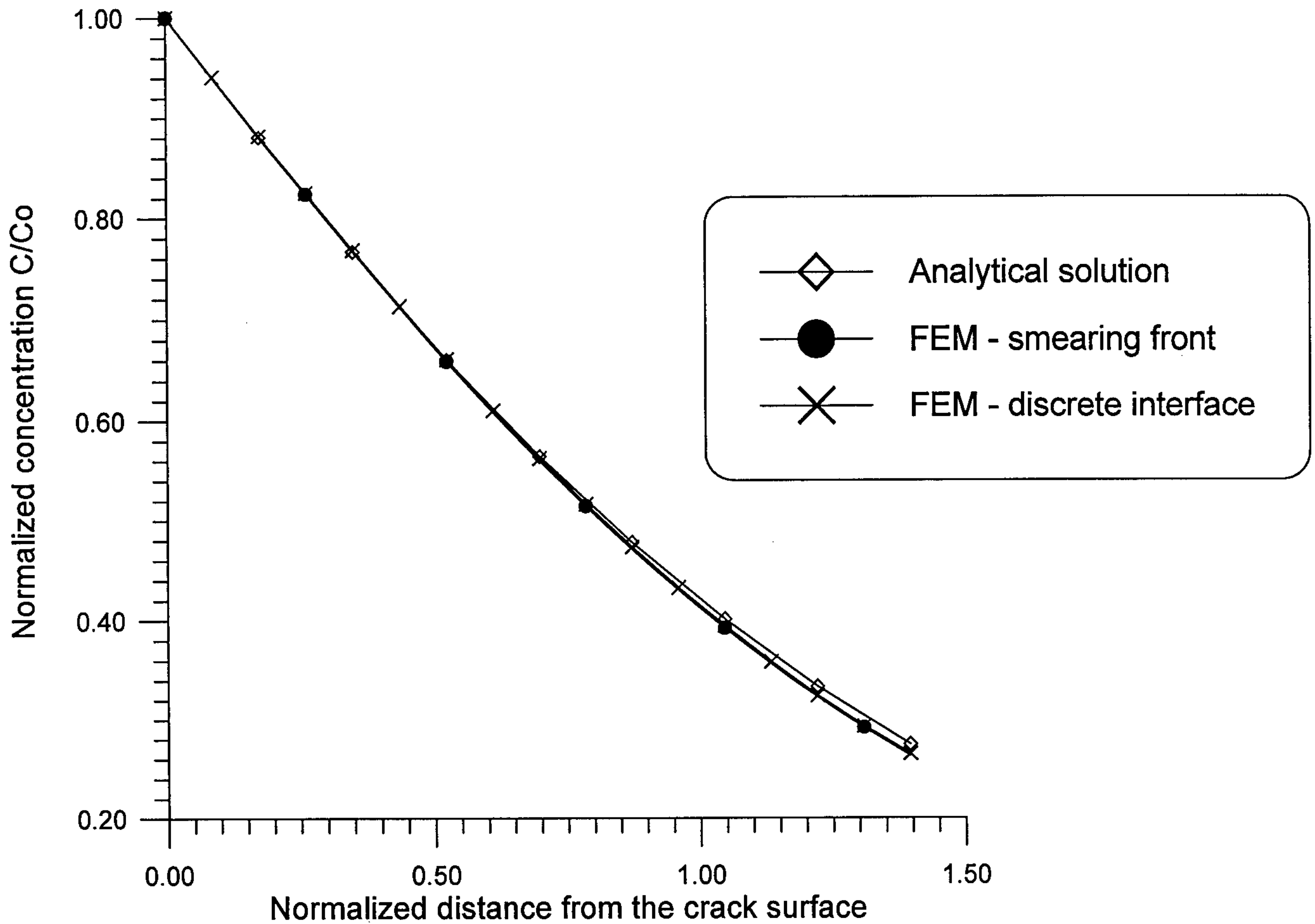


Figure 20. Comparison of oxygen concentration profiles along x_2 perpendicular to the crack surface.

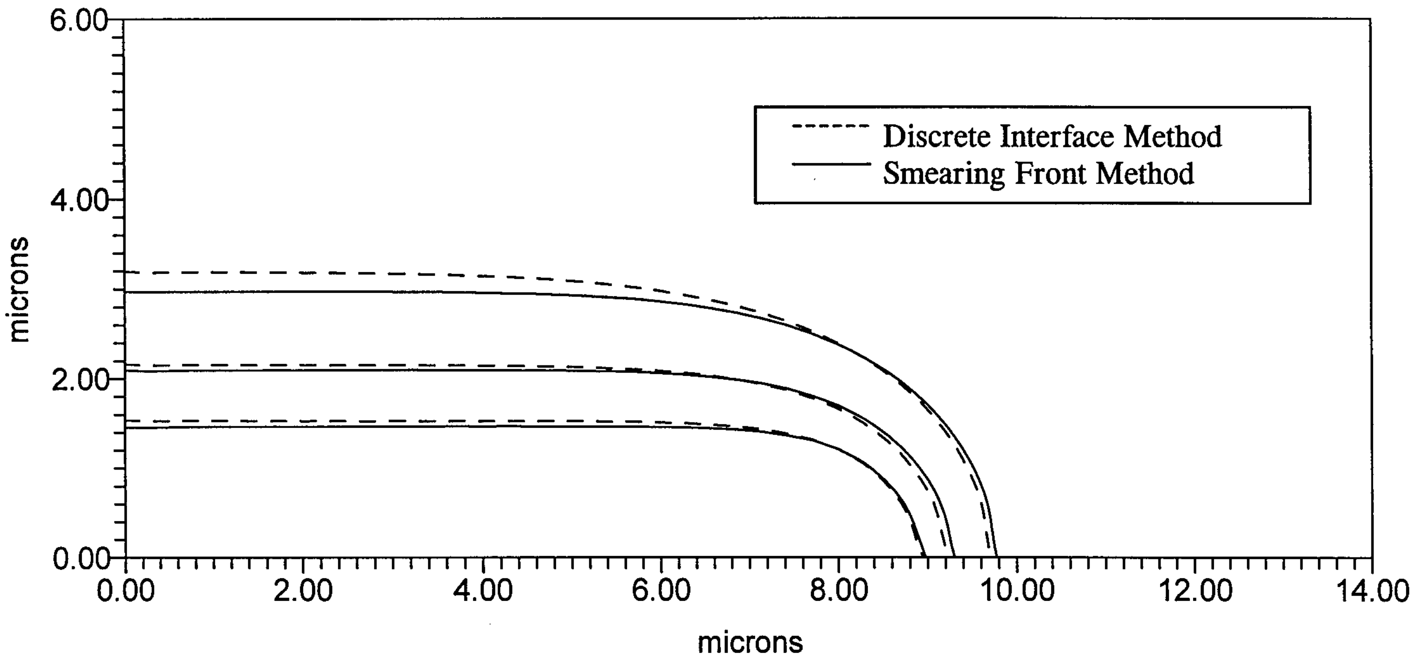
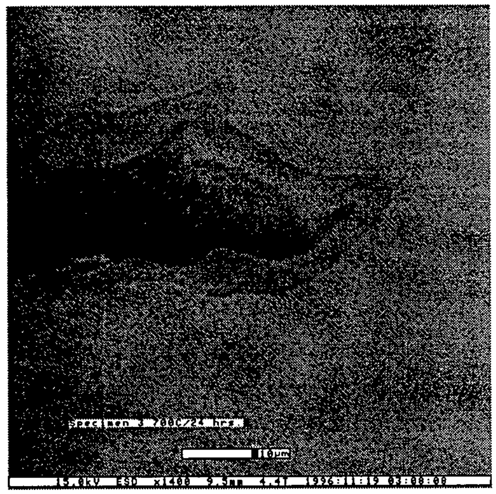


Figure 21. Simulation of the location of the oxidation front in an oxidized Ti-15-3 specimen at 700°C after 0.25 hours, 0.5 hours, and 1 hour.



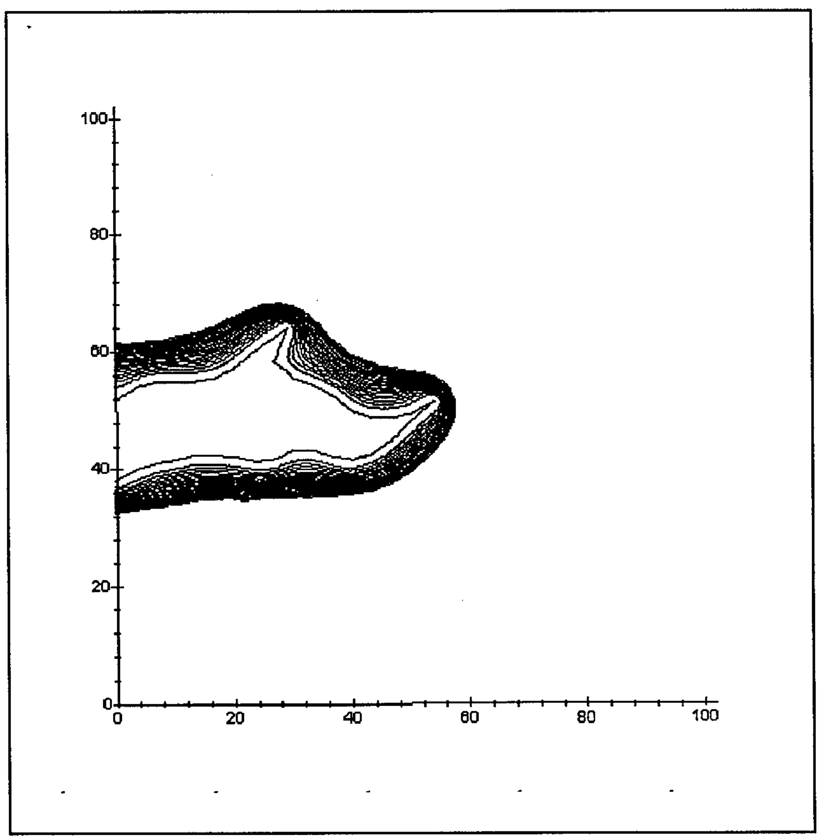


Figure 22. Simulation of crack tip in oxidized Ti. Actual crack tip shown above with simulation below it.